DEVELOPMENT OF AUTOMATED MOMENT TENSOR SOFTWARE AT THE PROTOTYPE INTERNATIONAL DATA CENTER

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ABSTRACT

We are porting automatic seismic moment tensor software used by the Berkeley Seismological Laboratory to the Prototype International Data Center (PIDC). This software package utilizes a surface wave spectral amplitude and phase method coupled with a three-component waveform inverse method that is scaleable from teleseismic to regional distances. The objective is to initially develop automatic software for the analysis of Mw5.5 and greater events on a global scale utilizing the International Monitoring System (IMS). For regions of specific interest we will utilize crustal structure calibration information from other DTRA projects to refine capabilities to Mw4.5 and greater. Currently version 0.1 is ported to the PIDC, and several examples of its use are presented. During the course of this project a staged testing program will be employed to refine the software and to provide robust code suitable for operations at the PIDC.

KEY WORDS:

Source parameters, seismic moment tensor, automated seismic analysis, discrimination

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OBJECTIVE

On a global scale approximately 10,000 magnitude 4 events occur annually and therefore automated seismic analysis systems are needed to quickly review the seismicity to monitor the CTBT. The objective of this project is to adapt and port to the Prototype International Data Center (PIDC) a set of codes developed and routinely used at UC Berkeley (Romanowicz et al., 1993; Dreger and Romanowicz, 1994; Pasyanos et al., 1996) to determine seismic moment tensors and source depth of seismic events automatically and close to real-time. While these codes are being used at UC Berkeley to monitor the strain release in natural earthquakes in northern California, the moment tensor inversion approach provides a potentially powerful discrimination procedure in several ways: (1) by providing estimates of M_w (moment magnitude), a more accurate measure of event size than Ms which can then be used along with M_L to construct magnitude ratio discriminants (e.g. Woods et al., 1993); (2) by providing estimates of source depth, which will help distinguish natural events (depths typically >> 1km) from nuclear explosions and (3) by providing estimates of radiation pattern characteristics (i.e. deviations from the typical double-couple radiation of earthquakes).

The initial performance goal of the ported software is the automated determination of moment tensors on a global scale for larger events (M>5.5-6.0) with a reduced threshold in a specifically targeted region. Later releases of the software will incorporate calibration information for several regions of interest, allowing moment tensor determinations at a lower magnitude threshold of approximately M~4-4.5.

RESEARCH ACCOMPLISHED

The two moment tensor codes used at UC Berkeley to monitor central and northern California earthquakes have been adapted to run at the PIDC, extracting all waveform data, event information, and instrument responses from the PIDC database (version v. 0.1). The adaptation of the codes to their current functionality, illustrated below, has met with several challenges, which required the development of signal processing code to remove SAC2000 dependency, and code to handle different instrument response formats that are used at the PIDC.

Two seismic moment tensor methodologies are run in parallel for two primary reasons; 1) to provide redundancy in the event that circumstances detrimental to any one methodology does not preclude the determination of a seismic moment tensor; 2) and to provide a means of automatically checking solutions for quality (e.g. Pasyanos et al., 1996).

The first methodology we use is a frequency domain, surface wave approach, adapted from the two-step method of Romanowicz (1982), for which calibrated fundamental mode surface wave phase velocities, in the period range 10-60 sec, are used for propagation corrections (Pasyanos et al., 1996). This method utilizes surface waves, which are the largest of the regional phases allowing for the analysis of smaller seismic events, and inverts the observed azimuthal variation in surface wave amplitude and phase for specific periods. We are able to analyze events to a magnitude of 3.5 using Berkeley Digital Seismic Network stations in the 100 to 500 km distance range. With sufficient azimuthal coverage this method is found to perform quite well.

The second methodology we employ is a time domain waveform fitting procedure that utilizes the entire long-period (T>20 seconds) wavefield (P_{nl}, S_n, Love and Rayleigh) (Dreger and Romanowicz, 1994; Pasyanos et al., 1996; Fukuyama et al., 1998; Fukuyama and Dreger, 2000). For the majority of events in northern and central California, two 1D crustal/upper-mantle velocity models are adequate. The operation of the code in Japan (NIED) is accomplished with a

single calibrated velocity model for the entire region (Fukuyama et al., 1998; Fukuyama and Dreger, 2000). With this method data from a single station is often sufficient, however in practice we use three-component data from 2 to 3 stations to improve the azimuthal coverage of the focal sphere (Pasyanos et al., 1996).

Examples of the Execution of the Moment Tensor Codes at the PIDC

Example #1: 06/01/98 event in Kamchatka

The analysis of surface wave spectra at seven stations for the 06/01/98 event in Kamchatka (Figure 1a) yields a thrust event (M6.4) consistent with the convergent tectonics of the region. A depth minimum exists at roughly 40 kilometers, similar to the reported Harvard CMT centroid depth of 35 kilometers.

Two primary stations were available within 5000 kilometers, BJT and HIA (2800 & 3600 km respectively). For this example, we have concentrated on the body wave portion of the record. The spherical reference model Green's functions used (IASP91) have difficulty matching the dispersion of surface waves for short paths and the relatively short periods used. We have also used the instrument responses from the PIDC database. Although the similar azimuth of the two stations essentially reduces the problem to a single-station analysis, the inversion retrieves an M6.4 thrust event (Figure 1b) with an optimal depth of 40-50 kilometers, consistent with the surface wave results. Close examination of the waveform fits indicates additional errors in the Green's functions; the early and late body wave arrivals cannot both be aligned with the kernels used.

Example #2: 06/14/98 event in Honshu, Japan

For a moderate event in Japan both the surface wave analysis (Figure 2a) and the complete waveform inversion (Figure 2b) retrieve a normal-type event. The surface wave inversion identifies a depth minimum of roughly 40 kilometers, in contrast to the shallow centroid value of 15 reported by Harvard. JMA reports a depth of 50 km and the moment tensor solution of the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED) yielded 26 km. The body wave inversion utilized two stations BJT and HIA at distances of 2200 and 2300 km respectively. There is difficulty explaining the vertical component data but a mechanism consistent with the surface wave analysis was obtained. The estimated moment magnitude is roughly a quarter of a unit lower than that estimated using surface waves, but is only 0.1 magnitude unit different than the solution reported by NIED (http://argent.geo.bosai.go.jp/freesia/event/hypo/joho.html). The normal mechanism obtained by the three-component body waveform inversion (Figure 2b) compares quite well with the NIED result.

Examples of Events with Volumetric Source Components

The moment tensor inversion at regional distances offers promising possibilities of distinguishing primarily double-couple solutions, typical of tectonic earthquakes, from solutions with significant non-double-couple or isotropic components, as would be expected from man-made explosions (or in some cases, of volcanic earthquakes). Figure 3 is adapted from Dreger and Woods (2000) and shows a comparison of moment tensor solutions obtained for the Little Skull Mountain earthquake (06/29/1992; M_W=5.6) and the Bexar nuclear explosion at the Nevada Test Site (04/04/1991; M_W=4.5). Both events were observed at two TERRAscope broadband stations at distances greater than 300 km. At the time of the Little Skull Mountain earthquake it was possible to use the four broadband stations shown in Figure 3a. At the time of the Bexar explosion only the PAS and PFO stations were available. We were able to demonstrate for the Little Skull Mountain earthquake that the solution obtained using only PAS and PFO was essentially identical to the solution obtained with greater than two stations (Dreger and Woods,

2000). Figure 3b shows that a full moment tensor inversion (one that allows for an isotropic component) of the tectonic Little Skull Mt. earthquake results in only a nominal isotropic component (88% double-couple, 5% CLVD, 7% isotropic). In contrast the full moment tensor inversion for the Bexar nuclear explosion yields a very anomalous radiation pattern that is only 6% double couple (Figure 3c). The moment tensor solution is dominated by a CLVD component and has a 28% isotropic component that indicates volumetric expansion. It may be surprising that the isotropic component is as small as it is however Patton (1988) demonstrated that for nuclear explosions it is not possible to distinguish between an isotropic component and a vertically oriented CLVD (both do not radiate significant SH waves) using long-period surface wave data. Several other NTS nuclear explosions with different levels of tectonic release were studied and it was found that the complete three-component waveform method yielded relatively shallow source depth and anomalous radiation characteristics that identified the events as suspect.

In a recent study of Mammoth Lakes, California seismicity (Dreger et al., 2000) statistically significant evidence of volumetric sources has been observed. Figure 4 shows the locations of broadband stations used in the analysis, and seismic moment tensors that were determined from the five closest Berkeley Digital Seismic Network stations. These stations provide more than 100 degrees of azimuthal coverage, which is an adequate sampling of the focal sphere using three-component records. We have performed a significance test on the improvement in fit afforded by both deviatoric non-double-couple and full moment tensor solutions including an isotropic component compared to a pure double-couple null hypothesis. In this analysis we have found that the improvement in fit that is obtained by the full moment tensor is significant at the 99% level using the F statistic to evaluate the difference in variance for two models. Furthermore a 'Jackknife' test demonstrates that solutions are extremely stable and are not biased by specific stations or station geometry. This study showed that noise in the inversion can produce isotropic components at the 10% level, however for the anomalous events the isotropic component (>30%) is shown to be statistically significant demonstrating that volcanic regions with relatively shallow seismicity may present substantial challenges in the monitoring of the CTBT.

CONCLUSIONS AND RESEARCH PLAN

We have successfully ported the UCB seismic moment tensor codes to the PIDC (v. 0.1) and have demonstrated their application to a number of far-regionally recorded moderate earthquakes. In addition, we have investigated the resolution of non-double-couple components of the seismic moment tensor, particularly the isotropic component for a number of western US earthquakes and NTS nuclear explosions. The results for the nuclear explosions indicates that recovery of a pure isotropic solution is not possible (e.g. Patton, 1988) and because of the presence of tectonic release. For a swarm of M4.5 earthquakes in the Long Valley Caldera we have recovered statistically significant volumetric components (Dreger et al., 2000).

The current project was initiated on July 20, 2000 and involves the stepwise development and refinement of automated seismic moment tensor software at the PIDC. The stages involve the testing of the present version (v. 0.1) on seismicity recorded by the IMS for a period of 3 months. Results from the test will be used to refine the algorithms, and Maxwell Technologies will provide software development support to port the system into the PIDC computing environment, yielding v. 1.0. v 1.0 will be 'frozen' and tested in an operational testbed environment for a period of 3 months. Results from the test will be used to further refine the algorithms, and Green's functions will be tuned for regions of specific interest resulting in v. 2.0 of the software, for which we will submit a Configuration Control Board (CCB) proposal for implementation.

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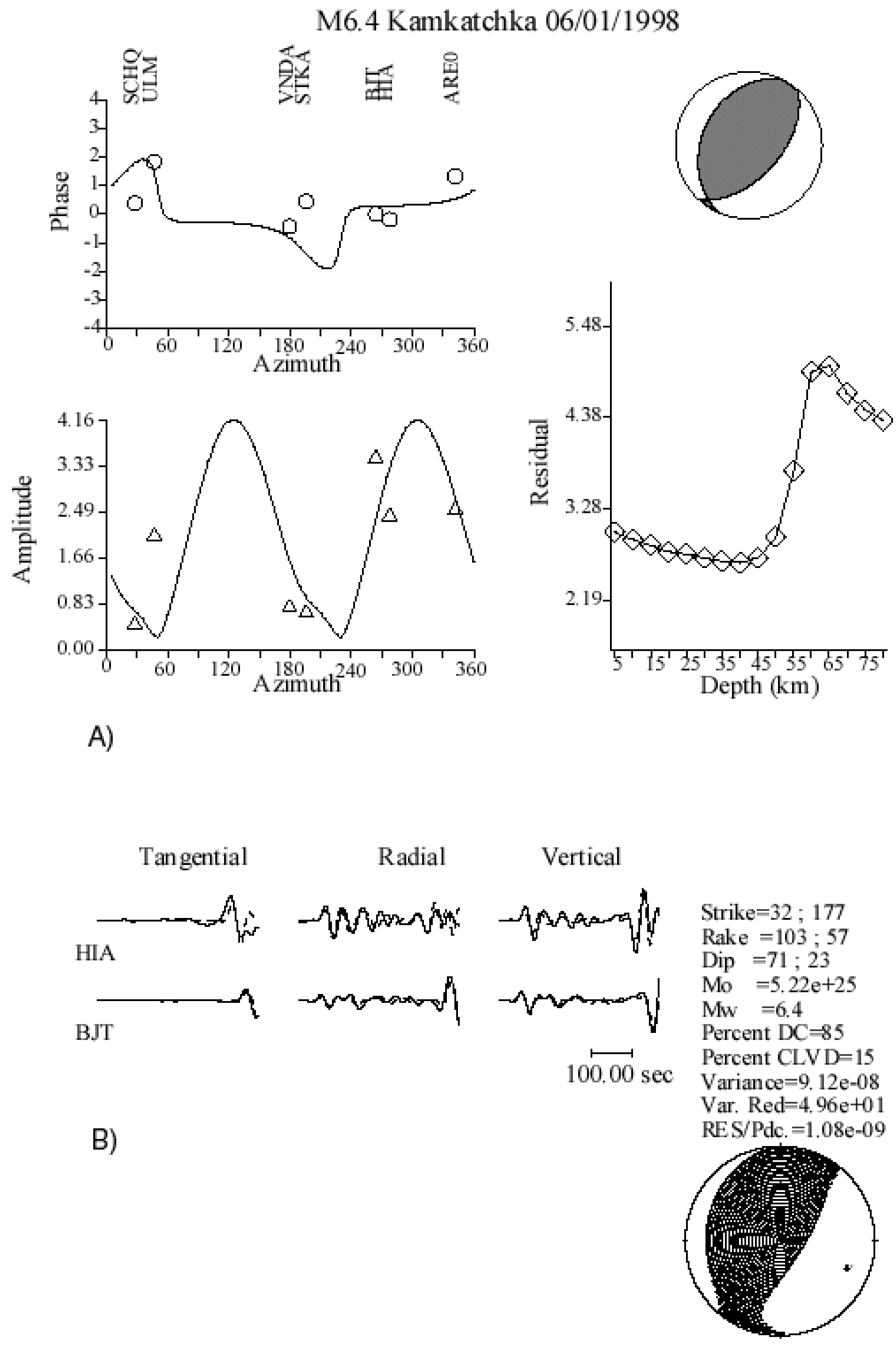

Figure 1. Example of inversion results for a Mw6.4 event in Kamchatka on 06/01/1998. A) Surface wave spectral amplitude & phase observations (circles) are compared to predictions for the shown mechanism. The resolution of the event depth is shown. B) Example of a two station, three-component body waveform inversion for the same event. Data is solid and synthetic is dashed. Only IMS stations were used in these analyses.

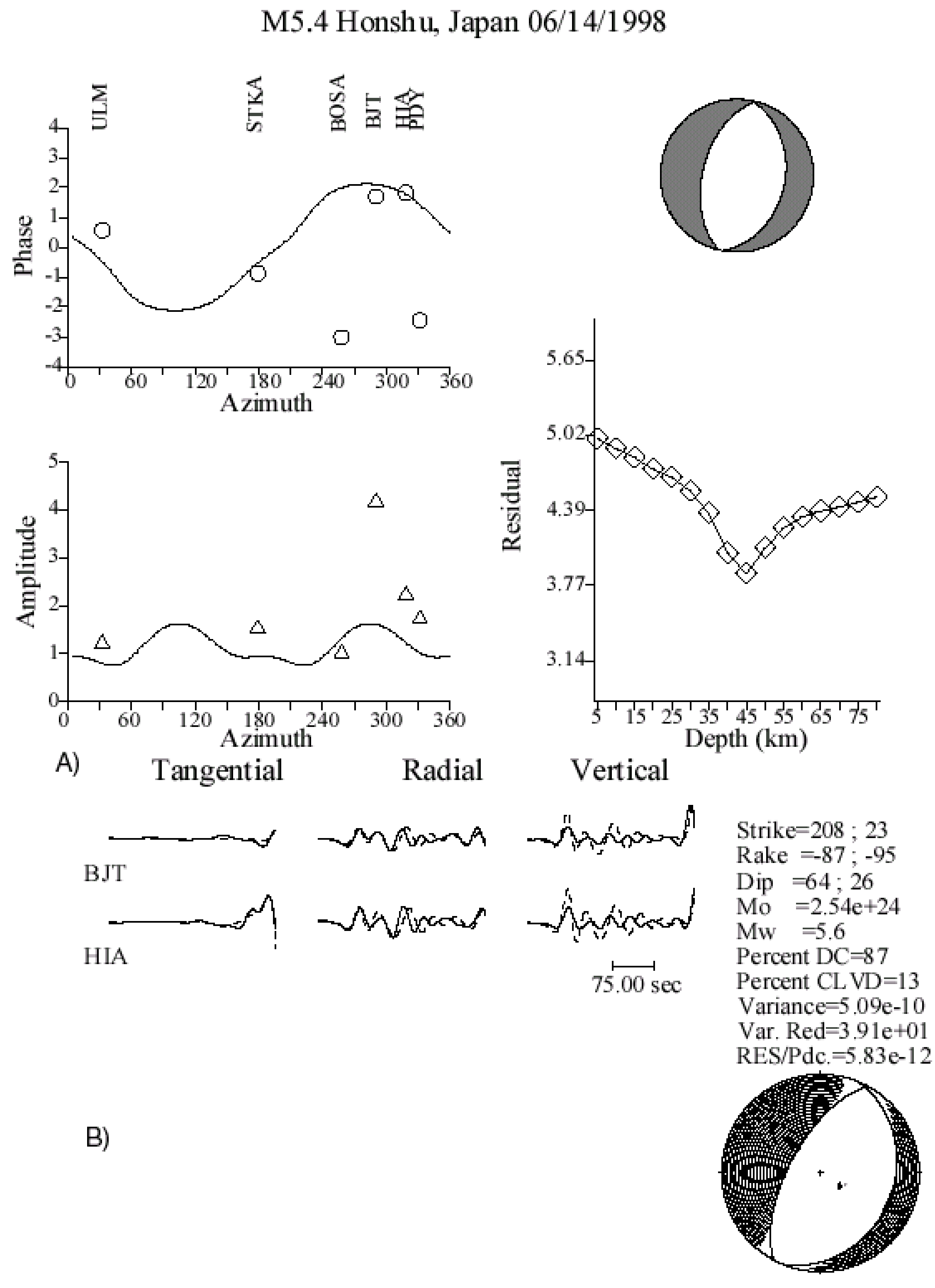

Figure 2. Example of inversion results for a Mw5.6 event in Honshu, Japan on 06/14/1998. A) Surface wave spectral amplitude & phase observations (circles) are compared to predictions for the shown mechanism. The resolution of the event depth is shown. B) Example of a two station, three-component body waveform inversion for the same event. Data is solid and synthetic is dashed. Only IMS stations were used in these analyses.

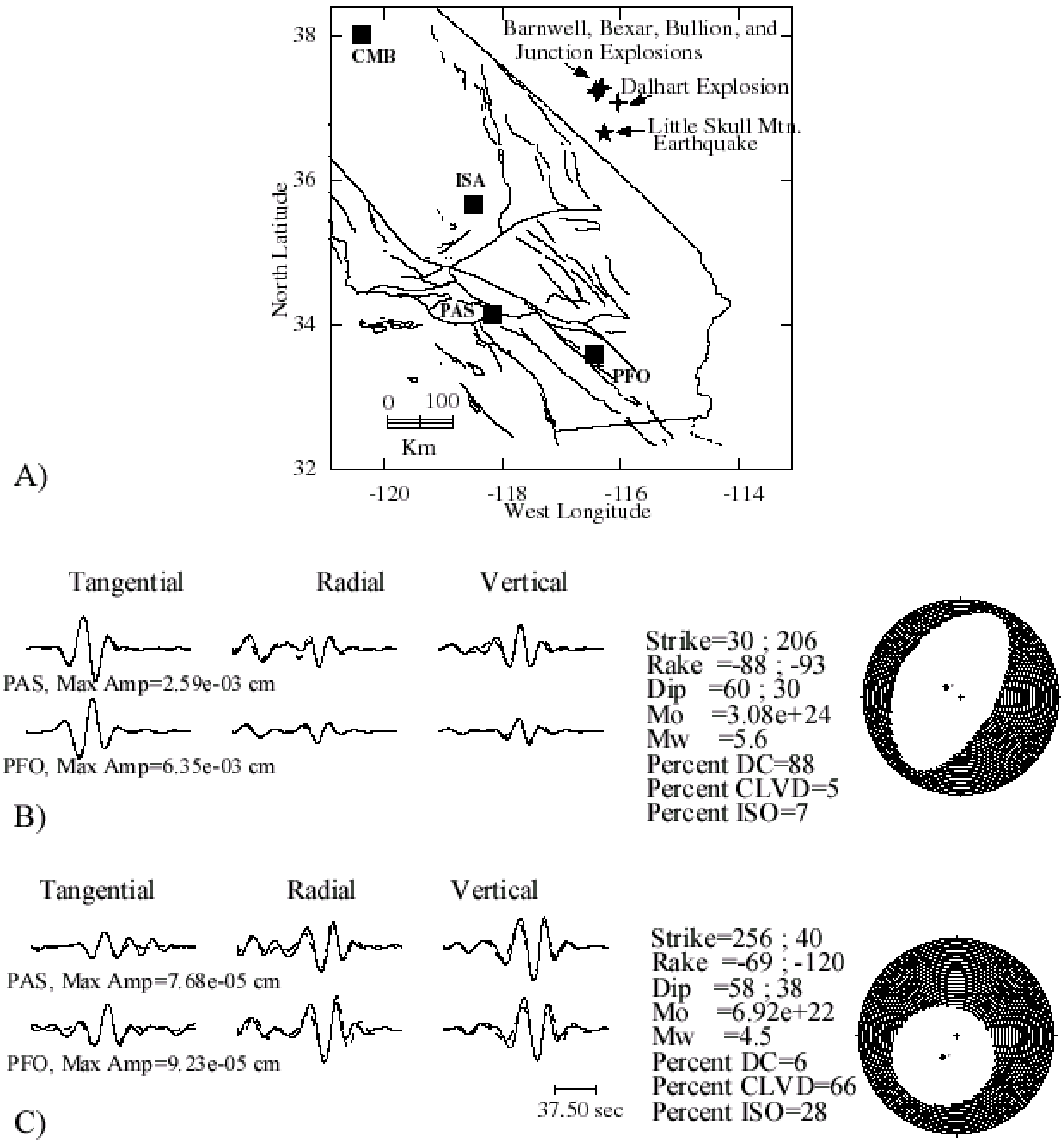

Figure 3. A) map showing the locations of broadband stations (squares), Little Skull Mt. Reference earthquake (star) and NTS explosions studied by Dreger and Woods (2000) (plusses). B) Complete moment tensor inversion of broadband displacement data for the Little Skull Mt. Earthquake. Note the nominal isotropic component. C) Complete moment tensor inversion for the BEXAR nuclear explosion. Note the unusually small double-couple component.

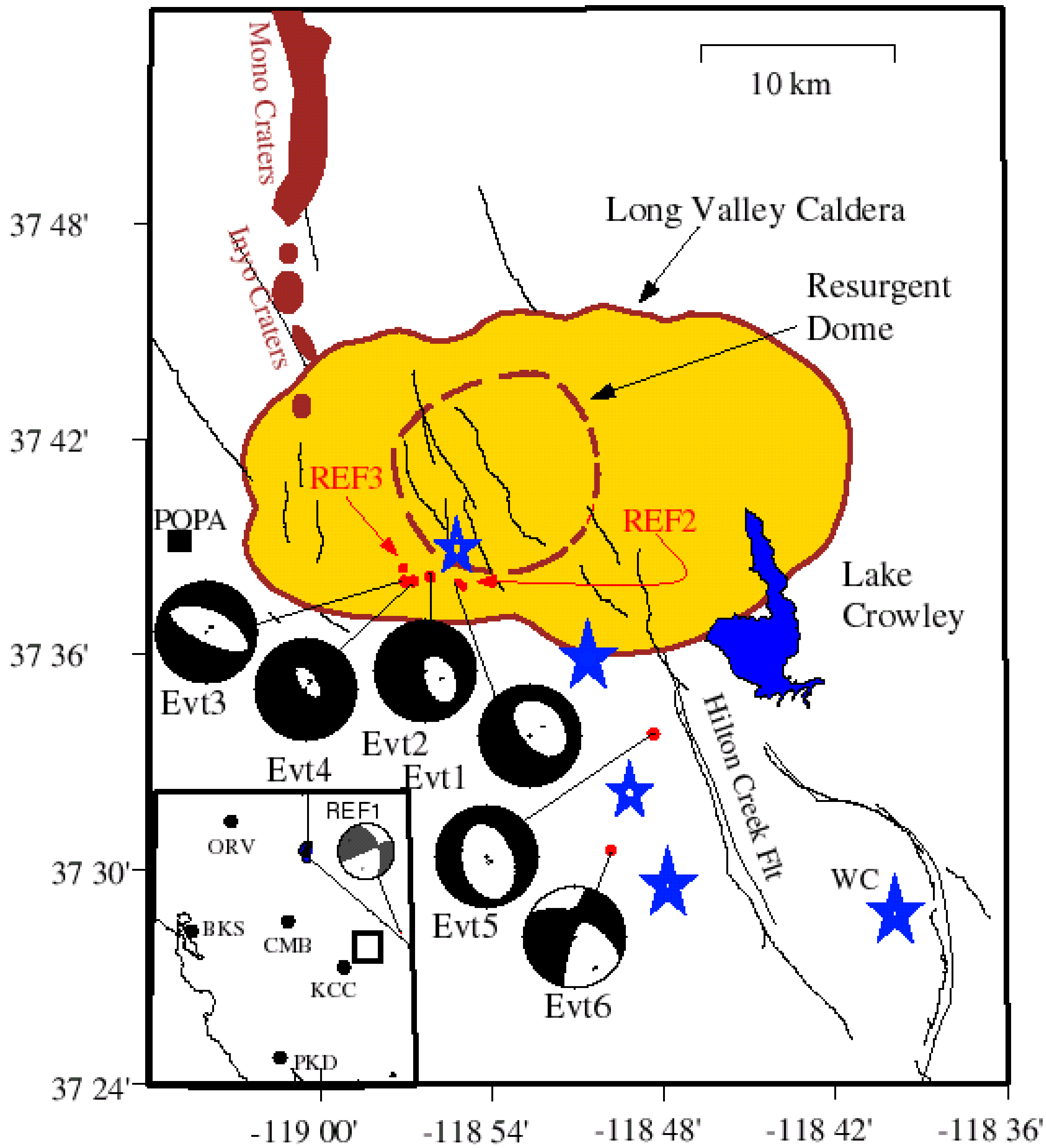

Figure 4. Map showing the Berkeley Digital Seismic Network, the Long Valley Caldera region (square) and a western Nevada reference earthquake (inset). The map of the Long Valley Caldera shows the locations of 1997 seismicity (red dots) in relation to caldera structure such as the resurgent dome, mapped faults, and the Inyo Craters chain. The blue stars show the locations of non-double-couple (filled) and double-couple (open) events of the 1978-1980 Long Valley swarm. The P-wave radiation pattern for the full moment tensor solutions for the 1997 events are shown. REF1, EVT5 & EVT6 are events located outside the caldera margin that have small, statistically insignificant volumetric components. The moment tensors for these events are primarily double-couple. EVT1-4 have anomalous seismic moment tensors with statistically significant volumetric components.